PROJECT ID: ELT260

Improving the Freight Productivity of a Heavy-Duty, Battery Electric Truck by Intelligent Energy Management

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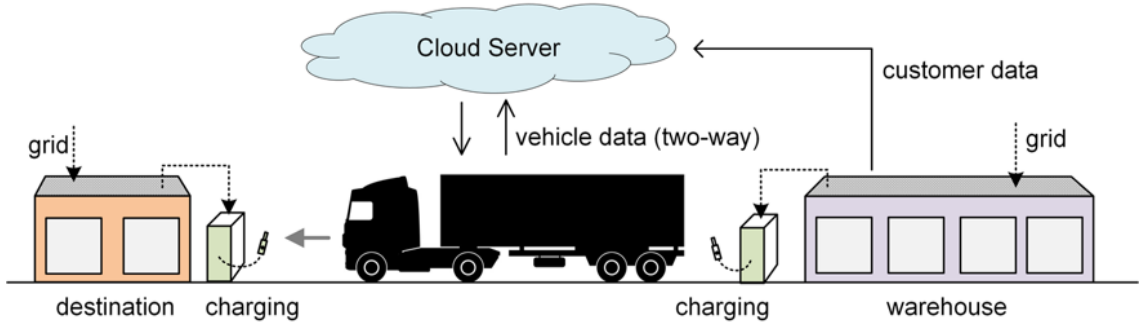
June 23, 2021



2021 DOE Vehicle Technologies Office Annual Merit Review

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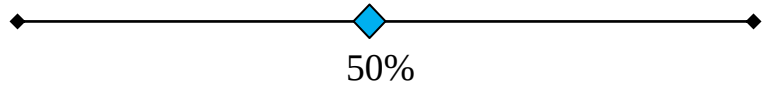
Project Overview

Timeline:

Oct. 2019 — Dec. 2022



50%

Funding:

Total Project Cost: $4,869,889

- DOE funds: $3,799,536
- Industrial cost share: $1,070,353

- FY2020 funding: $468,245
- FY2021 funding: $3,221,498

Partners:

- University of Minnesota
- HEB Companies
- Murphy Logistics

Barriers:

- Total cost of ownership:
  - High purchase price and range of charge and payload
- Performance Validation:
  - Fleets need better performance data on Battery Electric Trucks, (BEVs), in real-world usage to validate the reliability of the vehicles
- Infrastructure Needs:
  - Infrastructure cost and planning complications

VOLVO

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UNIVERSITY OF MINNESOTA
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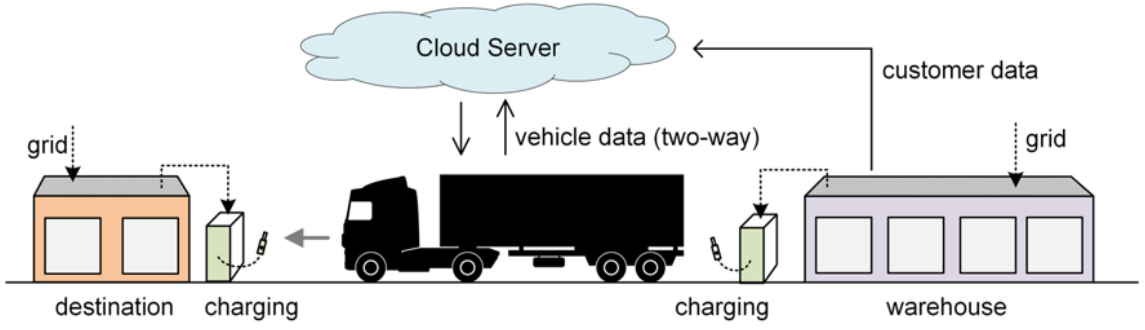
MURPHY LOGISTICS

Relevance

Impact:

Decrease the cost and time required for on-route charging, recommend energy efficient routing, and provide eco-driving recommendations to the operator.



Objective:

Research, develop, and demonstrate life cycle cost-effective Class 8 battery electric vehicles equipped with an intelligent Energy Management System (i-EMS) capable of commercial operations of ≥250 miles per day as well as increased efficiency and productivity when compared to baseline 2019 Mack and 2015-2020 Volvo heavy duty battery electric vehicle fleet performance.

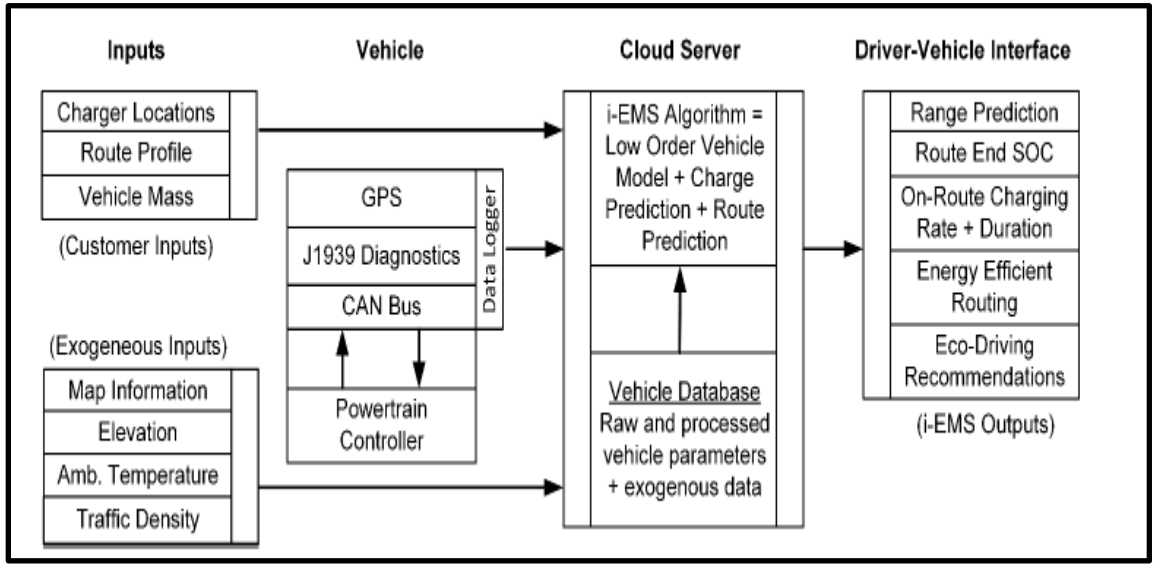
Milestones

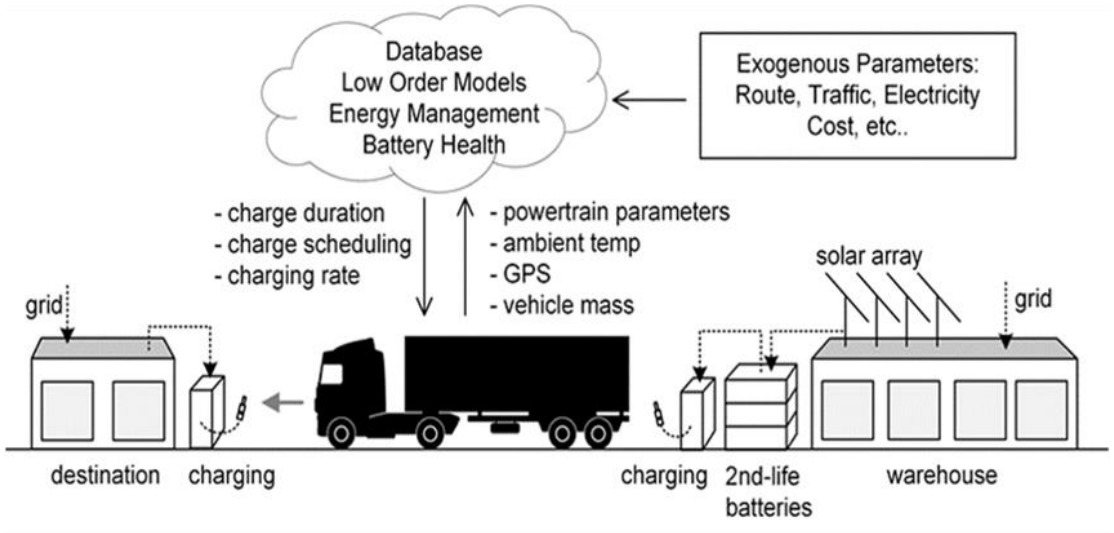
BP	Milestone	Type	Description	Status
Budget Period 1	Baseline database is created	Technical	Baseline database is created for all vehicle data and representative duty cycles are defined for the project	Completed
	Battery Electric Truck specification	Technical	Battery Electric Truck specification is ordered for build and delivery. Verified to Achieve Performance Measures, i.e., proper battery configuration.	Completed
	Initial battery electric truck simulation model	Technical	Initial, physics based battery electric truck model is complete	Completed
	Begin development of machine learning algorithm	Technical	Initial data and discussion allows for development of core algorithm to begin.	Completed
	Published verification plan and project requirement document	Go/No-Go	Published verification plan and project requirement documents outlining demonstration and evaluation plan is completed	Completed
Budget Period 2	Beta algorithms meet performance requirements.	Technical	Beta algorithms meet performance requirements to enable initiating of software development, i.e., identify and minimize on-route charging cost.	In-Process
	Completed energy-efficient routing and driving algorithms	Technical	Completed energy-efficient routing and driving algorithms	In-Process
	Driver interface app	Technical	Complete driver interface app to install on test vehicles that communicates with vehicle and cloud server	In-Process
	i-EMS performance	Technical	i-EMS performance is verified with actual truck operation per duty cycle definition	In-Process
	On-route charging locations	Go/No Go	Define necessary on-route charging locations for each customer site to accomplish the 250-mile range objective	In-Process

Approach

- Understand fleet partners' baseline operations and establish project duty cycles
- Combine physics-based truck model, battery information, utility demand charges and database parameters as inputs to a machine learning algorithm that will predict energy use, operational energy cost, and battery performance
- Implement i-EMS on 2 Battery Electric Vehicles, (BEVs), using a low-distraction screen to display charging and routing recommendations to operators
- Install vehicle charging locations at fleet partners
- Demonstrate i-EMS in daily operations with fleet partners covering both cold and hot-weather conditions

Schematic describing the flow of inputs and vehicle data





Technical Accomplishments and Progress

Overview

Task 1: Requirements & Planning

Task 1.4 Place purchase order for build of truck demonstrator

Task 2: Technology & Algorithm Development

Developed Elements of Intelligent Energy Management Strategy:

Task 2.1: Low-order physics model for fast energy estimation

Task 2.2: Initial machine learning algorithm for range and minimum charging prediction

Task 2.3: Eco-routing algorithm for use on filtered road network graph

Task 2.4-2.5: Charger placement optimization for individual trucks and routes

BEV Specifications

- Truck #1 (NME-6)
  - GEN2 Batteries

Description	NME-6 (Chassis# 604596) (Phase 1)	NME-8 (Phase 2)
INSTRUMENT CLUSTER GENERATION	-	IC-GEN1
CHARGING POWER	CHP150	CHP250
ENERGY STORAGE SYSTEM CAPACITY	ESS265K	ESS565K
ONBOARD CHARGER	ONCHAR	ONCHAR2
AIR COMPRESSOR DRIVING MOTOR	ACDM-AIC	ACDM-WC
COOLING ENERGY STORAGE SYSTEM	CESS-P	CESS-A
VEHICLE OVERSPEED,ALL COND,LOG	-	VOSAC70
ELECTRICAL SYSTEM	ELS-BP	ELS-BP+
PEDAL RSL SETTING	PRSL93	UPRSL

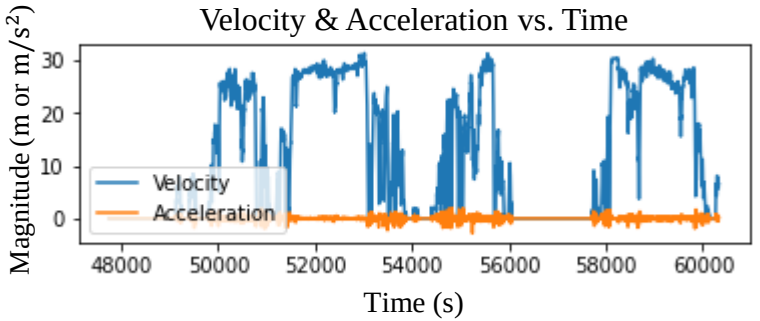
- Truck #2 (NME-8)
  - GEN3 Batteries

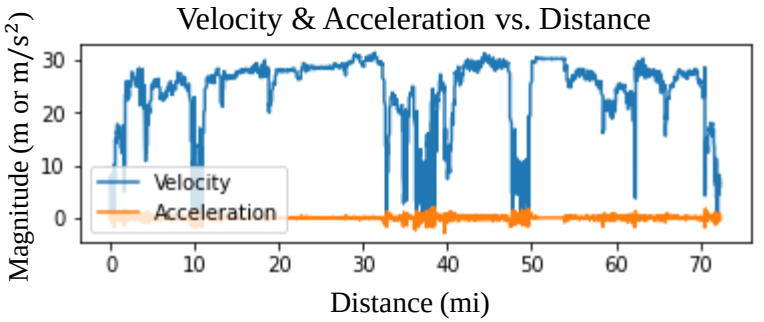
- Truck #1 is scheduled for delivery to Minnesota by August 2021
- Truck #2 is scheduled for delivery to Minnesota end of year 2021

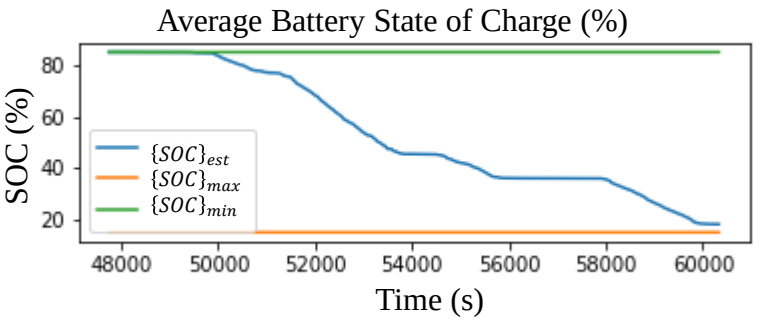
Technical Accomplishments and Progress

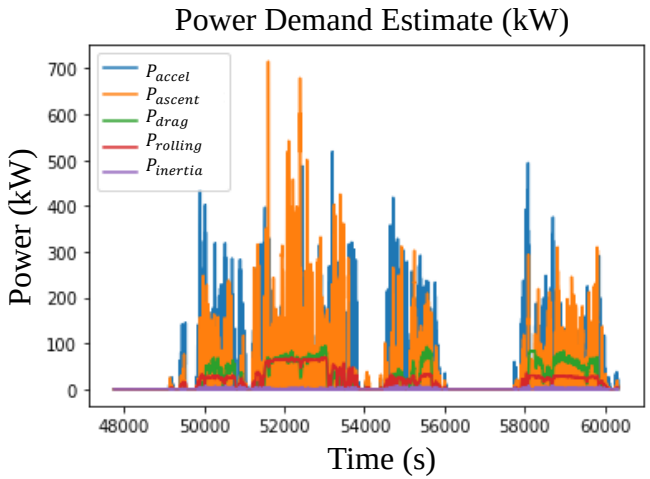
Task 2.1: Vehicle Physics Model

- Road Load Equation
  - Instantaneous Power
    - Acceleration
    - Ascent
    - Aerodynamic drag
    - Rolling resistance
    - Tire inertia
    - Braking friction losses
- Low-Order Battery Model
  - Current Delivered to Load
    - Open-circuit voltage
    - Internal resistance
    - Power demand





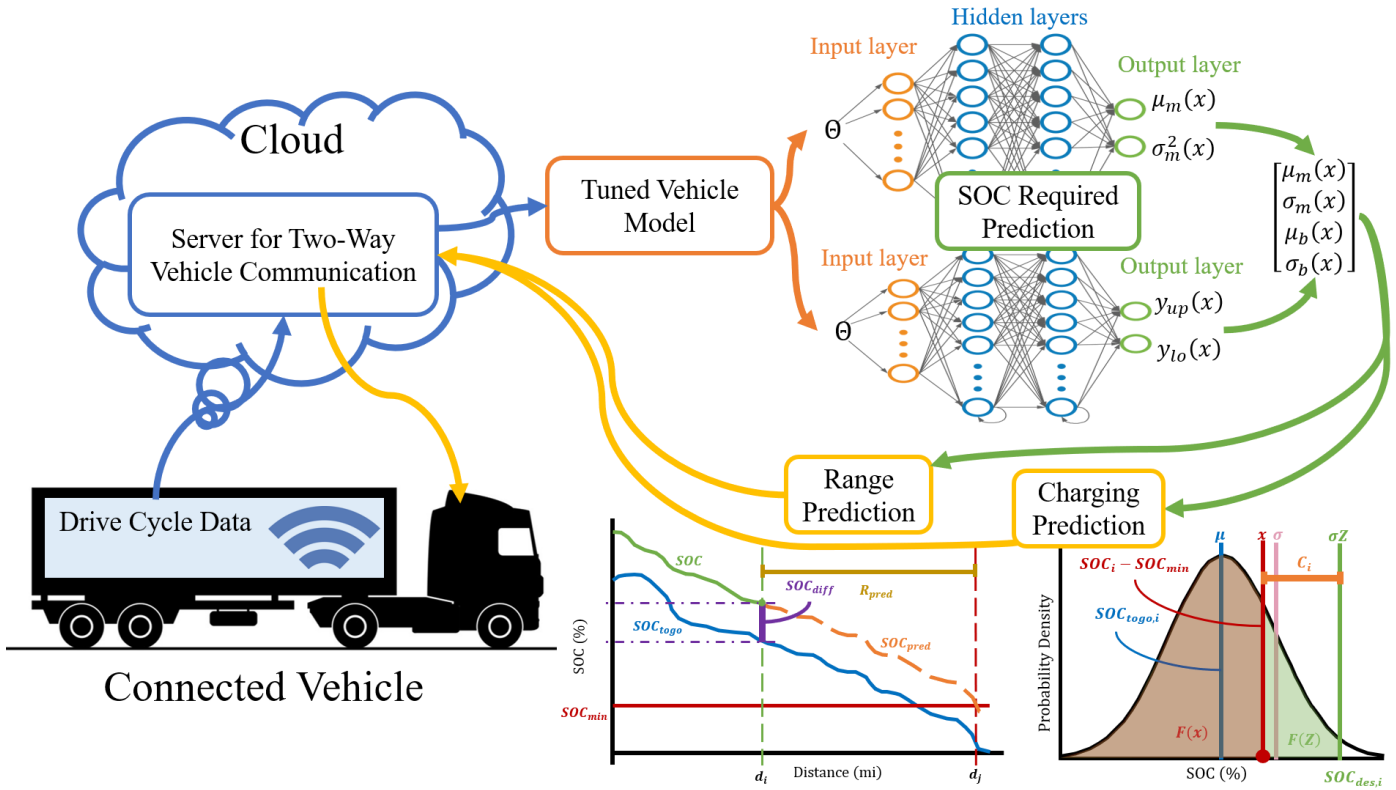


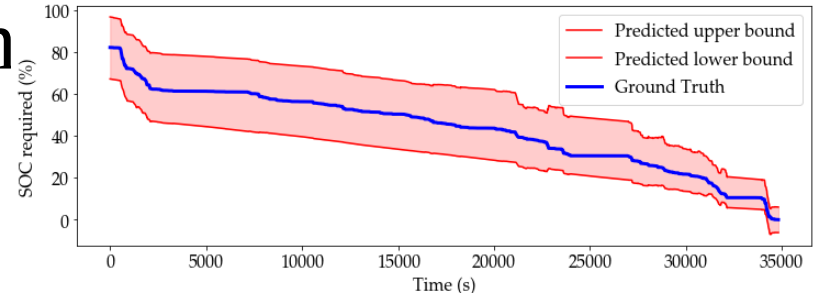


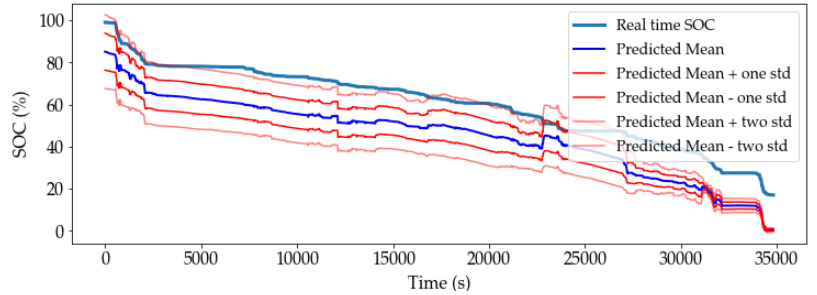
Technical Accomplishments and Progress

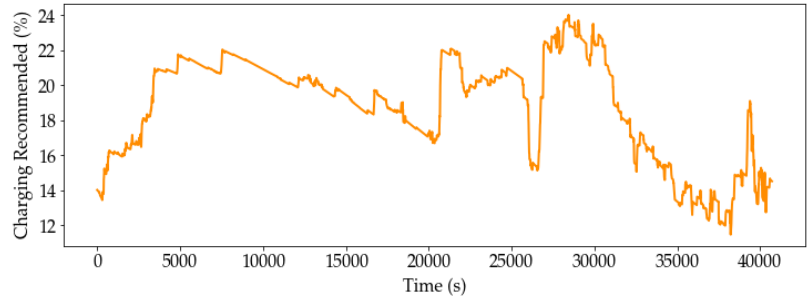
Task 2.2: Range and Charging Prediction

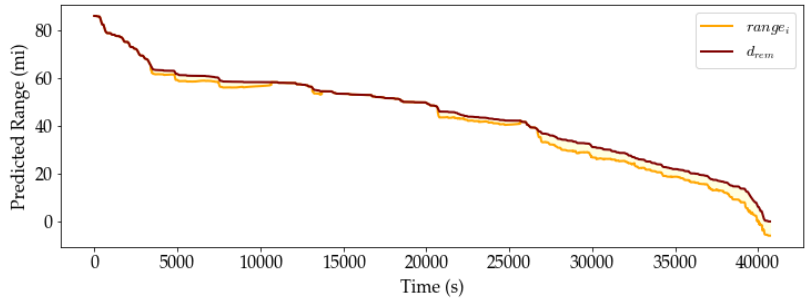
- Recurrent Neural Networks
  - Predict energy needed to complete route
  - Provide Statistical Confidence Measures









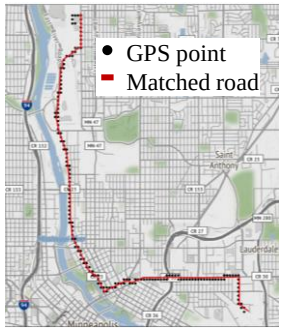


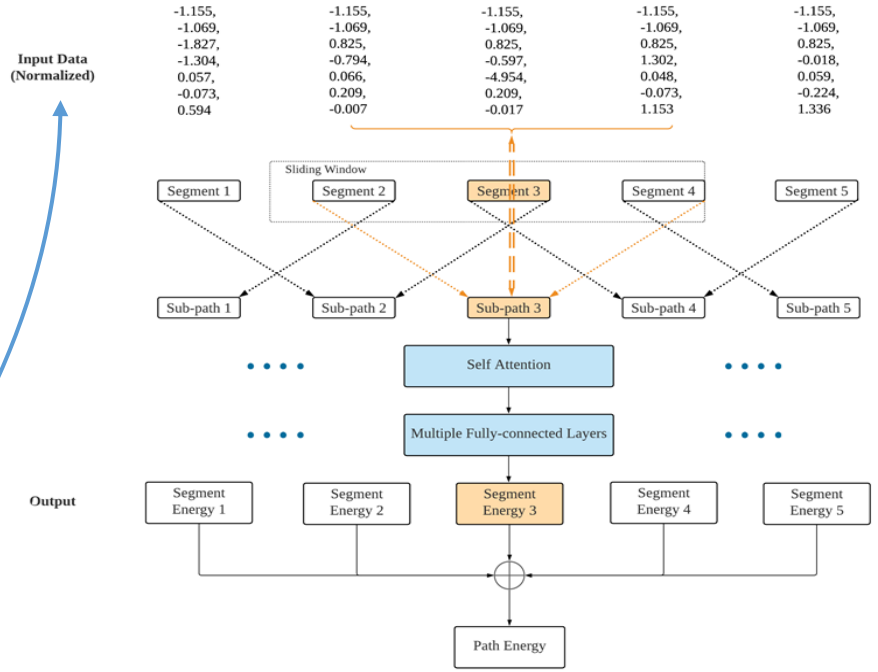
Technical Accomplishments and Progress

Task 2.3: Eco-Routing Algorithm

- Map-matching from GPS data
  - Road network graph construction
- Energy Estimation Methods
  - Energy Estimation Lookup Table
    - Energy estimation for similar road segment groups
  - Deep Neural Network
    - Energy estimation for individual paths

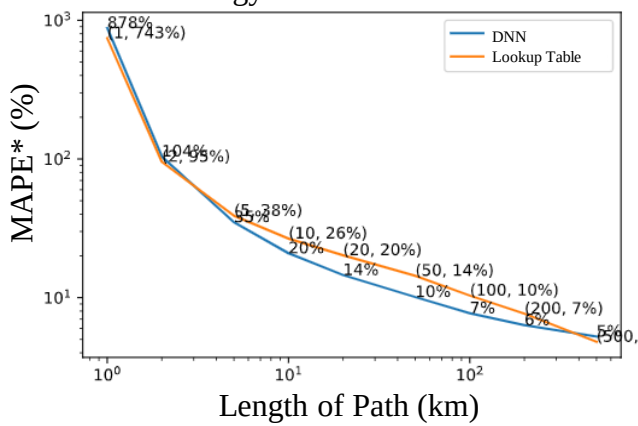
1. Road type
2. Speed limit
3. Elevation change
4. Previous orientation
5. Segment length
6. Direction of travel
7. Vehicle mass





- Routing Algorithm
  - Based on [1]

Energy Estimation MAPE*



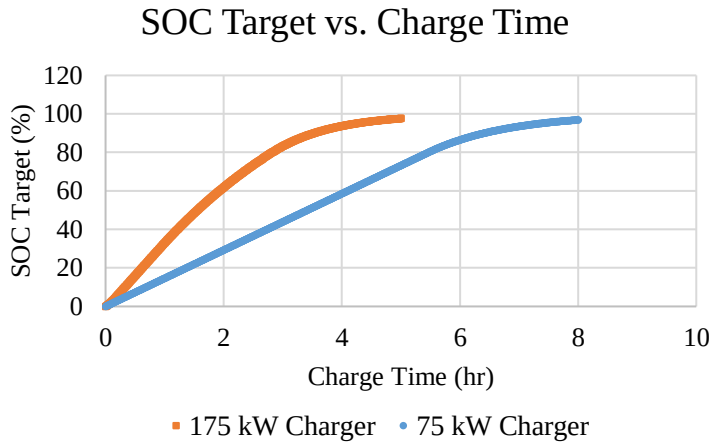
* Mean Absolute Percentage Error

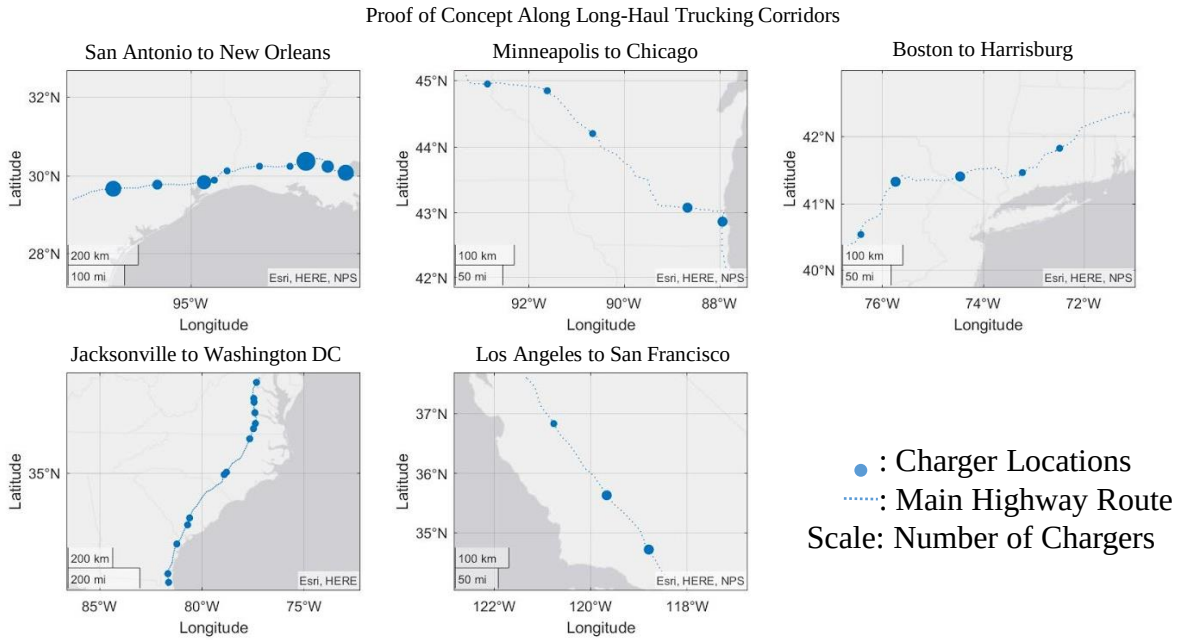
[1] Li, Yan, Pratik Kotwal, Pengyue Wang, Yiqun Xie, Shashi Shekhar, and William Northrop. 2020. Physics- guided Energy-efficient Path Selection Using On-board Diagnostics Data. ACM Trans. Data Sci. 1, 1, Article 1 (January 2020), 29 pages. https://doi.org/10.1145/3406596

Technical Accomplishments and Progress

Task 2.4-2.5: Charger Placement Algorithm

- Mixed Integer Programming Method
  - Optimize Placement Based Upon Expected Demand
  - Also Tested: Genetic Algorithm for Optimization Step
  - Incorporates Model-Based Driving Simulation
    - Vehicle Model
      - Drives along routes
      - Determines hotspots for charging needs
    - Charger Model
      - Charge on-route vehicles
    - Cost Model
      - Labor
      - Charger (Materials)
      - Electricity
  - Increases Number of Chargers Until...
    - Minimum Portion of Routes Are Feasible
    - Maximum Budget is Reached





Collaboration and Coordination

Organization	Key Contributions
Volvo	Principle Investigator, Contract Management, Project Management and engineering resources for truck operation, data collection and route simulation
University of Minnesota	Vehicle to cloud data management, algorithm development, data analytics, secondary driver display
Gilbarco	Electric charging support, installation of chargers
HEB Companies	Fleet testing, operational data, driver feedback
Murphy Logistics	Fleet testing, operational data, driver feedback

Remaining Challenges and Barriers

- Technical Challenges
  - Handling sparse data collection on production vehicles
    - Adapting models to handle less frequent data – minimize performance loss
    - Collecting some additional data through sensors on driver-vehicle interface
  - In-house model validation with results from proprietary OEM models
    - Determining the effects of temperature on battery performance
    - Quantifying low-voltage battery behavior for Voltage-to-SOC relationship
    - Output power limiting behavior for charging stations
  - Fast road network graph generation through map-matching and filtering
  - Quantifying the effects of traffic on eco-routing

- Other Barriers
  - Slight delay in delivery of the BEV Trucks to the Fleet partners
  - Slight delays in the procurement of an electric charger
  - Defining accurate operational cost parameters
  - Identifying best routes for use in long-haul dominated trucking fleets

Proposed Future Research

- BP2: Energy Management Strategy Validation
  - Optimize vehicle model parameters for production vehicles
  - Develop further reinforcement/deep learning range prediction models
    - Investigate ability to make decisions on best time to re-route to chargers
  - Validate eco-routing algorithm using new energy estimation methods
  - Finalize charger placement solution for vehicle fleets
  - Deploy algorithms on driver-vehicle interface for testing and validation

- BP3: Testing and Operational Cost Analysis
  - Tailor developed models to maximize performance
  - Develop and investigate correctness of operational cost model
  - Evaluate most effective use-case for participating fleet partners
  - Gather feedback from vehicle operators on driver-vehicle interface

Any proposed future work is subject to change based on funding levels

Project Summary

- The goals of this project are aligned to the key barriers of total cost of ownership, performance validation and infrastructure needs as pertaining to the operation of a Heavy-Duty BEV.

- In this reporting period analysis has been performed on the baseline data to develop the i-EMS technologies that will be used to recommend energy efficient routing and provide eco-driving recommendations to the operator.

- Activity has started with the procurement of chargers and the charging infrastructure for placement at the fleet partners.